Design and Implementation of an IoT Control and Monitoring System for the Optimization of Shrimp Pools using LoRa Technology

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***Abstract*—The shrimp farming industry in Ecuador, renowned for its shrimp breeding and exportation, faces challenges due to diseases related to variations in abiotic factors during the maturation stage. This is partly attributed to the traditional methods employed in shrimp farms. Consequently, a prototype has been developed for monitoring and controlling abiotic factors using IoT technology. The proposed system consists of three nodes communicating through the LoRa interface. For control purposes, a fuzzy logic system has been implemented that evaluates temperature and dissolved oxygen abiotic factors to determine the state of the aerator, updating the information in the ThingSpeak application. A detailed analysis of equipment energy consumption and the maximum communication range for message transmission and reception was conducted. Subsequently, the monitoring and control system underwent comprehensive testing, including communication with the visualization platform. The results demonstrated significant improvements in system performance. By modifying parameters in the microcontroller, a 2.55-fold increase in battery durability was achieved. The implemented fuzzy logic system enabled effective on/off control of the aerators, showing a corrective trend in response to variations in the analyzed abiotic parameters. The robustness of the LoRa communication interface was evident in urban environments, achieving a distance of up to 1 km without line of sight.**

***Keywords*—Control and monitoring system; shrimp pools; IoT architecture; LoRa technology; fuzzy logic control**

I. INTRODUCTION

In recent years, there has been a remarkable growth in the aquaculture industry worldwide. One of the most prominent activities in commercial aquaculture is shrimp production. In this context, Ecuador has been a significant player due to its extensive coastline and longstanding tradition in shrimp farming. According to the 2020 Annual Report of the Instituto Nacional de Pesca (INP) of Ecuador [1], shrimp aquaculture is a strategic industry that contributes significantly to the country's economy.

Despite the favorable conditions for shrimp exports, not all shrimp farming companies have sufficient technology to meet the required care standards. This is because Ecuador faces limitations in technological development. The majority of patents in the country are focused on preventing viral and bacterial diseases [2].

That is why the use of techniques such as Fuzzy Logic, which allows intelligent and adaptive control in complex systems, using linguistic rules to handle uncertainty and inherent imprecision in aquaculture, is of vital importance. According to [3], the use of Fuzzy Logic has been effective for control and intelligent management of water quality in aquaculture. In this work, they developed a simulation approach in MATLAB for a fuzzy logic-based control system for freshwater aquaculture. On the other hand, in [4], they present a review of works that employ fuzzy logic control in aquaculture systems, and in [5], supported by fuzzy logic and IoT, they develop an intelligent system for monitoring and early warning of water quality for aquaculture.

Additionally, the incorporation of LoRa as a long-range wireless communication technology provides the capacity to transmit data efficiently and reliably, even in remote areas. By combining these technologies with IoT, it is possible to create a real-time monitoring infrastructure and a centralized platform that allows shrimp farmers to supervise and control the shrimp harvest from any location.

Several works have been developed considering the aforementioned approach, such as the study conducted in [6], which highlights the importance of Long Range IoT technologies for remote monitoring and data transmission. On the other hand, in [7], they apply this technology to the monitoring of aquaculture information, and in [8], they explore the same area, developing a control and monitoring system based on IoT using LoRa. In the same vein, in [9], they design a system for monitoring water quality in aquaculture based on LoRa, obtaining encouraging results. On the other hand, the greatest emphasis that needs to be implemented in companies focuses on the shrimp breeding stage, as it is during this phase that the highest number of diseases and deaths in the harvest occur [10]. Shrimp diseases of infectious nature include viruses, bacteria, fungi, and parasites, where water quality directly influences the susceptibility of shrimp to different pathogens. For this reason, one of the most crucial considerations during shrimp breeding is the control of water quality [11].

TABLE I. IMPORTANCE OF ABIOTIC FACTORS

Parameter	***Importance***
Dissolved Oxygen (DO)	Dissolved oxygen produces crises of hypoxia or anoxia.
pH	When it is out of normal range it can cause stress.
Temperature	This parameter is related to DO in an inversely proportional way. It influences parameters such as solubility, chemical reactions, and toxicity.
Salinity	Affects the behavior of dissolved oxygen.
Turbidity	The cloudier the water, more light is blocked, affecting photosynthesis.
Ammonium	In shrimp farms it can be found as ionized (and non-ionized)

The factors affecting water quality are segmented into three categories: abiotic factors, biological factors, and environmental factors. Among these factors, we will emphasize the abiotic factors for the study, as they have a significant impact on production and harvest. In Table I, the importance of different abiotic factors in aquaculture is evident [12], [13], [14].

As can be seen in the previous table, the different abiotic factors have their influence on other abiotic factors, such as the behavior and growth of the shrimp. Therefore, it is necessary for the abiotic parameters to be within an ideal range.

The ideal range of abiotic parameters is determined based on different criteria presented by various authors. Table II presents the ideal ranges of abiotic parameters according to different authors.

TABLE II. ABIOTIC FACTORS' RANGES

Ref	**Temp**		***Salinity***		***DO***		***pH***		***Nitrite***		***Ammonium***	
	Min	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***
[14]	-	29	-	-	4.0	6.0	6.0	9.0	-	0.09	1.22	2
[15]	29	31	10	13	5.0	-	7.0	8.5	-	0.1	-	0.1
[16]	28	30	15	25	6.0	10.0	8.0	9.0	-	0.1	0.1	1.0
[17]	26	32	-	-	3.7	-	-	-	-	0.1	-	0.12
[18]	26	32	15	25	5.0	-	7.0	9.0	-	0.3	-	0.3
[19]	25	30	15	25	4.0	-	6.0	9.0	-	0.1	-	0.1

Having abiotic parameters within a defined ideal range is considered a controlled environment. There are different consequences when shrimp are not in a controlled environment, meaning when the abiotic parameters are either above or below the range.

To minimize the effect of abiotic factors' variation on aquatic life, monitoring and control of these factors must be carried out [20]. As the demand for shrimp continues to increase and there is a quest to enhance efficiency and sustainability in aquaculture practices, adopting advanced technologies for control and monitoring of shrimp pools becomes crucial. In response to this growing demand, the present study develops a control and monitoring system based on Fuzzy Logic, LoRa (Long Range), and the Internet of Things (IoT) to address specific challenges faced by Ecuadorian shrimp farms. The approach combines these technologies to achieve intelligent and automated management of environmental conditions, maintaining an optimal environment for shrimp growth and development.

The rest of this manuscript is structured as follows: Section II presents a brief description of work related to the pond shrimp harvesting stage, abiotic factors, IoT architecture features, and the application of fuzzy logic. Section III describes the proposed methodology, the IoT structure, the devices to be used, the survey for the equipment selection and the control system. Section IV presents the experimental results obtained with the designed control and monitoring system. Finally, Section V provides the conclusions of this study and states the future work.

II. RELATED WORKS

The problem encountered during the shrimp pond harvesting stage is not unique to Ecuador; it is also present in various shrimp-producing countries. This section addresses how different authors have dealt with this challenge, and in Table III, a brief description of related works is provided.

TABLE III. RELATED WORKS

Reference	***Description***	***Equipment***
[12]	Proposal of a fuzzy model for analyzing the internal parameters of shrimp pools, describing the water status qualitatively.	-
[13]	Proposal for an analysis of water quality to control crises in aquatic systems.	-
[21]	Real-time modeling of a vehicle for shrimp pools, using fuzzy logic algorithms.	pH sensor. DO sensor. Temperature sensor. Turbidity sensor. Arduino Uno. Node MCU.
[22]	Evaluation of feeding strategies for shrimp based on fuzzy logic and mathematical functions.	Applied in a test laboratory. The simulation of the models was done using MATLAB.
[23]	Improving feeding conditions through the use of passive acoustics, computer vision, and telemetry.	Automatic feeder. Hydrophone. Controller. Wireless Communication.

In the work developed in [12], they established different categories for water quality based on abiotic parameters, which were obtained using fuzzy logic. From related literature, they determined that organisms are susceptible to diseases as a consequence of shrimp stress (variations in internal parameters of the pools). Fuzzy logic is considered an effective tool to assist shrimp farmers. In another research [13], it is mentioned that water quality is essential for proper shrimp growth, as they are susceptible to stress due to their ecosystem conditions. Other authors [14] indicate the importance of maintaining the ranges in which the abiotic parameters are found. These parameters are used to produce a quality index. On the other hand, in [21], they achieved a precision of 92% in the applied test to predict the water status. The control algorithm was based on fuzzy logic, and the authors anticipate that implementing such elements in a shrimp pond will improve conditions. According to [23], having a better understanding of feeding techniques improves the conditions in which shrimp grow. Having a monitoring system in shrimp pools results in an increase in economic returns, as it allows better control of different parameters. The focus of that study was on feeding techniques, with a hydrophone being the selected equipment to analyze the ideal time for shrimp feeding.

A. IoT Architecture

An IoT architecture allows interconnection and communication between different devices by establishing a connection with the cloud. It is not necessary for the devices to be physically located in the same place; instead, the monitoring and visualization of various processes can be done from different platforms [24]. In a shrimp farm where access to technology is challenging, implementing IoT architecture concepts offers many advantages and benefits. Fig. 1 illustrates the characteristics that these services provide.

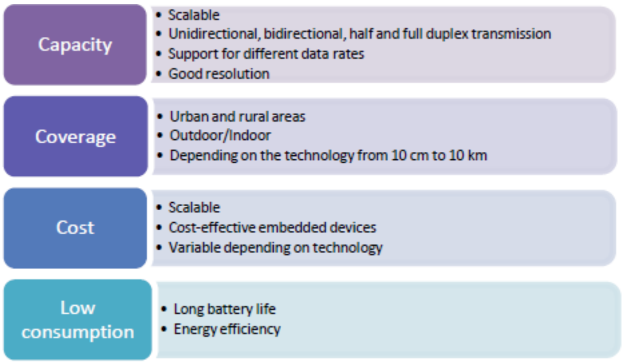

Fig. 1. Characteristics of IoT.

Wireless access networks within the IoT architecture vary and depend on the solution that will be provided to a specific problem, determining which one to use. Fig. 2 illustrates the coverage distance of different networks.

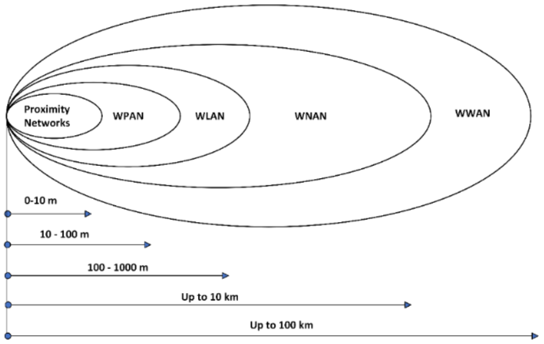

Fig. 2. Wireless access geographic coverage. Proximity networks, Wireless Personal Area Networks (WPAN), Wireless Local Area Networks (WLAN), Wireless Neighborhood Area Networks (WNAN) and Wireless Wide Area Networks (WWAN) [24].

The focus lies in the fact that different communication protocols have their limitations regarding their range. However, when a greater range is required, the use of Low-Power Wide Area Networks (LPWAN) within the can be employed. When considering the range that devices must have to communicate with each other, the modulation and transmission rate must be carefully analyzed [25]. Table IV presents different communication protocols found in the literature, such as LoRa, Sigfox, and Zigbee [26].

TABLE IV. DIFFERENT COMMUNICATION PROTOCOLS

Characteristics	***LoRa***	***Sigfox***	***Zigbee***
Power	Low [27]	Low [28]	Low [29]
Transmition range	10 km	3 to 50 km	10 to 100 m
Data Rate	0.3 to 50 kbps	100 to 600 bps	20 to 250 kbps
Modulation	Spread spectrum modulation type based on FM pulses.	Ultra narrow band radio modulation	DSSS as a spreading technique
Modulation Technique	Chirp-spread spectrum	BPSK	BPSK
Topology	Star/mesh/point-to-point	Star	Star
Security	Resistance to electromagnetic interference. Robust to multi-path fading.	Low Frequency Accuracy constraint. High resistance to interferences.	Access control list. Frame Counters Encryption of over-the-air communicactions [30].
Battery	Long battery life	Long battery life	Long battery life
Bandwidth	900 MHz <500 kHz	200 kHz 100 Hz	2.4 GHz 915 MHz 868 MHz

Among the various advantages offered by different physical layer protocols, the LoRa modulation technique stands out for providing enhanced security. The Chirp Spread Spectrum, commonly employed by the military and in communication security applications, is utilized in LoRa [31].

III. MATERIALS AND METHODS

LoRa communications can be modified and depend on different parameters, which can be configured in the application. These parameters include spreading factor, coding rate, transmission power, chirp polarity, and synchronization word. Due to the versatility LoRa offers in device-to-device transmission, it has been selected as the communication method for the study. The LoRa protocol will be used for intercommunication between the different nodes in the pools. Meanwhile, the internet module will be used in the gateway module for communication with the ThingSpeak platform, enabling real-time visualization of the abiotic parameters of the different pools, as shown in Fig. 3.

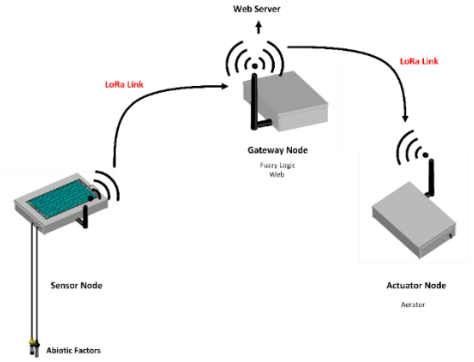

Fig. 3. Nodes.

In the gateway, the fuzzy logic function is embedded to calculate the next state of the aerator. The sensor nodes are enabled for data transmission, while the actuator nodes are enabled for data reception. The gateway node is configured to receive information from the sensor node and send information to the actuator node.

A. Control

In the process control field, there are different techniques for implementation, and one common type of controller is the PID controller, which provides a fast dynamic response. However, it requires control calibration for events with high precision, and one of its disadvantages is its high sensitivity to noise. An alternative control type is fuzzy logic, which consists of two stages: fuzzification and defuzzification (see Fig. 4).

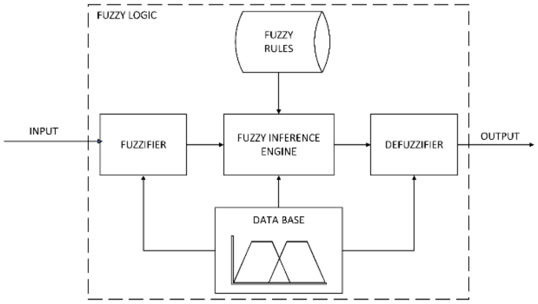

Fig. 4. Fuzzy logic.

The inputs to the controller first go through the fuzzification process to obtain a fuzzy value. This value then goes through an inference mechanism, which is complemented by fuzzy inference rules and fuzzy functions (database). Depending on the fuzzy input values, a fuzzy output value is obtained, which is then transformed into a real value through the defuzzification process.

B. Survey

For the selection of equipment to be implemented and sensors for the prototype, a survey was conducted with 35 shrimp farmers located in the province of El Oro, Ecuador. The most notable data from the survey were as follows:

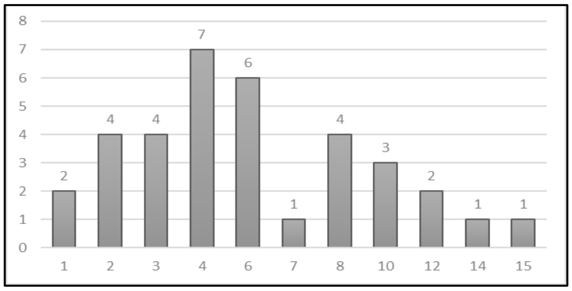

Fig. 5. Question 1: How many pools do you have?

The first finding pertains to the sizing of the pools and the scalability of the equipment. It is observed that the mode among shrimp farmers is to have four pools (Question 1). However, since there are shrimp farmers with 15 pools, the dimensioning of the devices to be connected in our monitoring network should be able to support and even have a larger capacity (see Fig. 5).

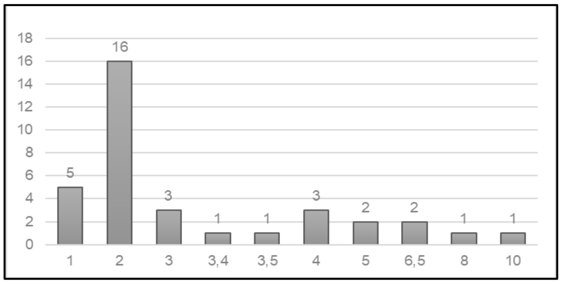

Fig. 6. Question 2: Size in hectares of your smallest pool

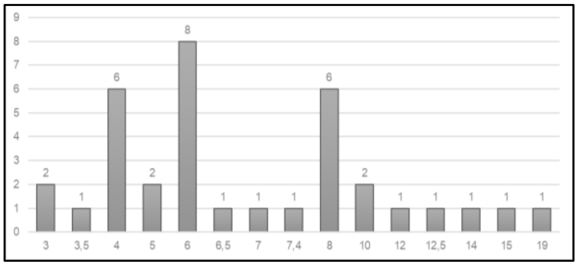

Fig. 7. Question 3: Size in hectares of your largest pool

Of the surveyed users, they were asked about the size of the smallest pools they have, and it was observed that they range from 1 to 10 hectares (Question 2) as shown in Fig. 6. Among these, 46% have a standard size of 2 hectares. When analyzing the case of the largest pools, they range from 3 to 19 hectares (Question 3) as depicted in Fig. 7.

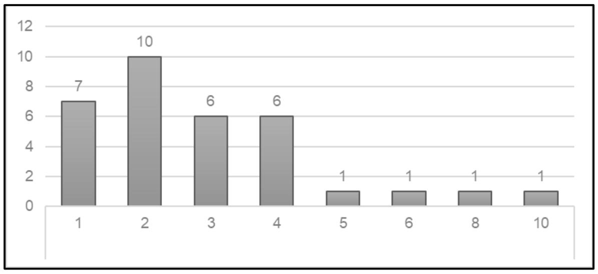

Fig. 8. Question 4: How many aerators do you have in your smaller pool?

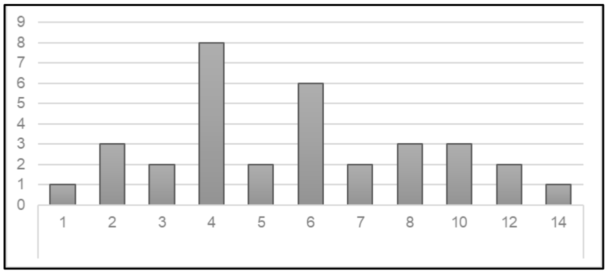

Fig. 9. Question 5: How many aerators do you have in your largest pool?

By knowing the size of the pools, we can identify how many devices or equipments are installed within each pool. It is observed that the range varies from 1 to 14 aerators (Questions 4 and 5 as shown in Fig. 8 and 9). Both points mentioned not only help determine how many pools are present but also give an idea of the number of devices that need to be installed and controlled in the pools.

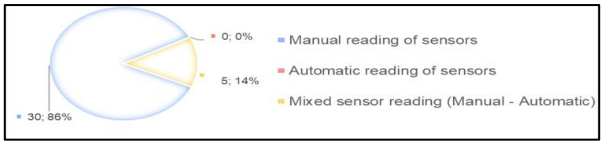

Fig. 10. Question 6: Indicate what kind of control mechanism you currently have implemented in your shrimp pool.

From the survey conducted with the shrimp farmers, it was determined that 30 of them perform the process of measuring parameters manually, while only five of them use both manual and automatic measurements (Question 6) as can be determined from Fig. 10.

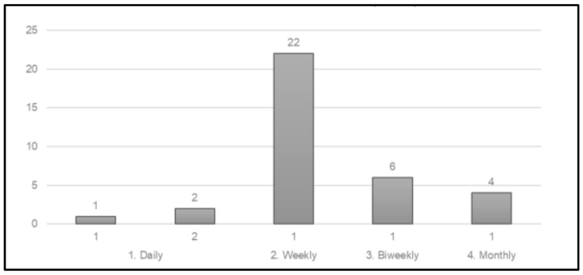

Fig. 11. Question 7: Measurement Frequency

A key question to determine the water quality among the surveyed shrimp farmers is that the measurement process is mostly done on a weekly basis, with only three shrimp farmers doing it daily. In the most severe cases, the analysis is done bi-weekly or monthly (Question 7) evident from Fig. 11. This information allows us to determine the focus of the final product to be developed.

C. Devices

For the selection of devices to be used, market devices were analyzed, and the summary is presented in Table V.

TABLE V. DEVICES

	Arduino Uno	***Arduino Nano***	***TTGO Lora32 Oled V1***	***Heltec WiFi LoRa32***
Chip	ATmega328P	ATmega328	ESP32	ESP32
Module	-	-	SX1276	SX1276
Processor	-	-	32-bit LX6	32-bit LX6
Transmission power	-	-	+20dB	+20dB
Transfer frequency	-	-	868-915 MHz	868-915 MHz
ROM	-	-	448 kB	448 kB
RAM	-	-	520 kB	520 kB
Flash Memory	16KB/32KB	32KB	4MB	8MB
Operating Voltage	5V	5V	2.7V-3.6V	3.3V-7V
Input Voltage	7V-12V	7V-12V	3.7V-4.2V	3.3V-7V
Input Voltage Limit	6-20V	-	-	-
GPIO	14	14	28	28
Analog Pins	6	8	-	-
PWM Pins	6	6	-	-
Clock Frequency	16 MHz	16 MHz	40MHz	40 MHz

In this way, by comparing the internal features of the devices, the TTGO LoRa32 Oled V1 model was selected, as it has a 32-bit processor and a 4MB flash memory. Although it has a smaller flash memory compared to the Heltec device, it still meets the needs for the sensor and actuator nodes. Having a low input voltage is favorable for achieving longer equipment autonomy.

D. Solution Description

For the monitoring and control of shrimp pools, the solution consists of a stage of measuring the abiotic parameters in the pond using a sensor node. Once the data is obtained, it is sent to a gateway node where it is processed using a fuzzy logic algorithm. This algorithm is designed to determine the next state of the pond's aerator (on or off). This value is then sent to an actuator node, which commands the activation of the aerator using a relay. A brief description of the process is shown in Fig. 12.

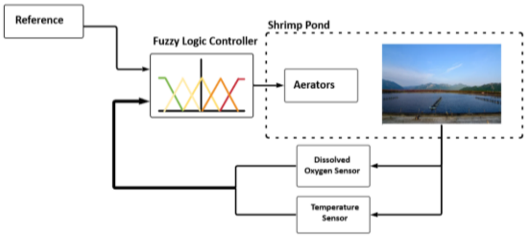

Fig. 12. Proposed control system.

The data obtained and used in this work are available at the following link: https://github.com/josep5097/LoRa-Shrimp-Monitoring-Control

As mentioned, the concept of the Internet of Things is used for the current model of the control and monitoring system. In Fig. 13, you can observe the structure of the proposed architecture.

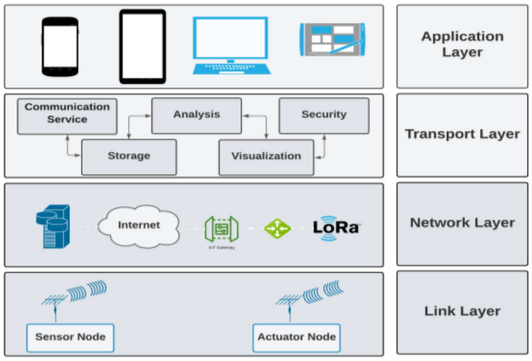

Fig. 13. IoT structure.

Within the link layer, there are sensor nodes and actuator nodes, and communication between the devices is through the LoRa protocol. When using the LoRa communication protocol, a topology must be chosen for the communication between devices. For the present system, a star network topology was selected over a mesh network. This decision was made because devices in a full duplex communication (mesh) require being powered on all the time, leading to a higher energy demand. An outline of the established architecture is shown in Fig. 14.

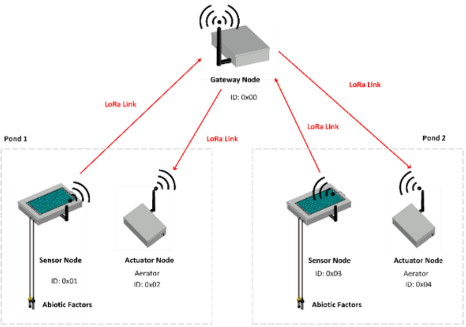

Fig. 14. Topology.

Within the network layer, there is a designated device to serve as our gateway to the Internet, in this case, the gateway node. It communicates with the different nodes in the pools using the LoRa protocol in its physical layer, and with the Internet using the HTTP protocol.

The devices have a synchronization word and ID, as shown in Fig. 13, which means that only devices with this synchronization word in their header can receive the message. Additionally, encryption was implemented to ensure that the messages transmitted by the LoRa devices are understood only by the intended receivers. To avoid signal interference, a gap between message transmissions must be established.

The captured data from the pools is visualized using the ThingSpeak platform, with the information being sent from the gateway device as described in Fig. 15.

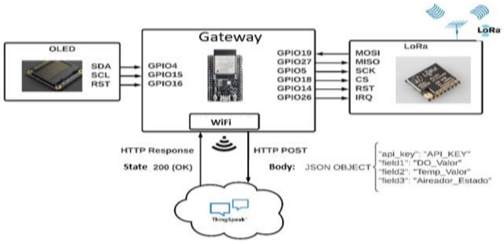

Fig. 15. Gateway connection.

In Fig. 15, besides the formation of the JSON object that is sent, you can see the pins used to connect both the OLED and the LoRa module. Similarly, the connection used with the sensor and actuator nodes is described. For the sensor node, GPIO pins are used for the dissolved oxygen and temperature sensors, as shown in Fig. 16.

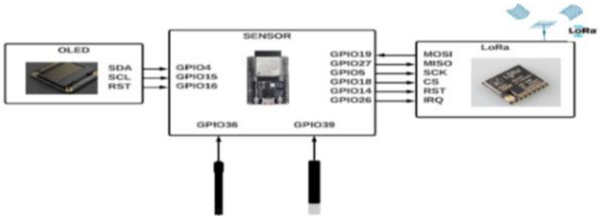

Fig. 16. Sensor node connection.

Meanwhile, for the actuator nodes, a GPIO pin is used to activate a relay for turning on or off an aerator (see Fig. 17).

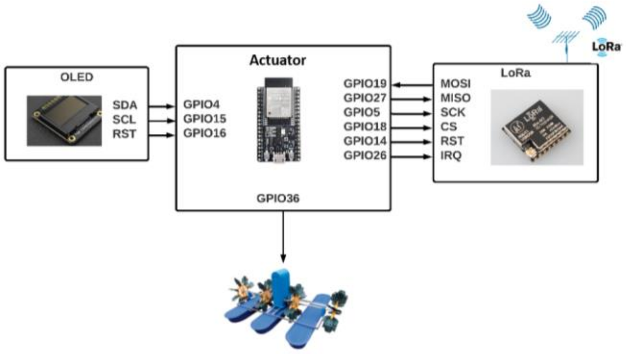

Fig. 17. Actuator connection.

E. *Pseudocodes*

To establish the described behavior of the devices in Fig. 15, 16, and 17, the processes are described using pseudocodes for each of the nodes.

Pseudocode 1: Nodo Gateway

```
# Init variables
DO [ ]= 0;
Temp [ ] = 0;
Aerators = 0;
# Init an array with all ID of nodes
ID_Sensors = {ID_S1, ID_S2};
ID_Actuators = {ID_A1, ID_A2};
# Init all variables in the fuzzy control
Fuzzy_Variables();
# Control Variables
num_Case = 1;
LoRa_Ok = false;
Void Setup {
        Fuzzy_Setup();
        LoRa.Setup();
        LoRa.begin();
        ThingSpeak.begin();
}
Void loop () {
        Switch (num_Case){
        case 1:
                LoRa_Read();
                If ( LoRa_Ok == True)
                num_Case ++;
                } else  {
                num_Case = 1;
                }
                break;
        case 2:
                controlDifuso(Do, Temp,Aireadores);
                num_Case++;
                break;
        case 3:
                comunicacionLoRaActuador(destino, origen,
                Aireadores)
                num_Case++;
                break;
        case 4:
                procesoThingSpeak (Do, Temp, Aireadores,
                ID_Piscina);
                num_Case = 1;
                break;
        }}
```

The monitored variables, such as DO and Temperature, are established along with the controlled variable, which is the Aerator. The Dissolved Oxygen and Temperature values will be obtained from a sensor node, and the state of the Aerator represents the next state of the corresponding actuator node in the pool from where the sensor node's parameters originated. The value for the Aerator state will be determined using fuzzy logic. To establish a relationship between the sensor nodes and actuator nodes, unique IDs are assigned.

1) Fuzzy logic configuration subprocess: The fuzzy control process is described in Fig. 18, the diagram of relationships between entities, in which it can be observed how the variables interact among functions.

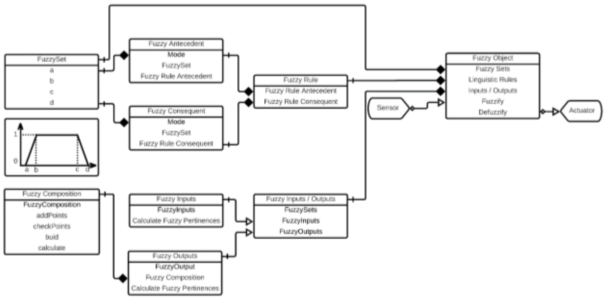

Fig. 18. Diagram of relationships between entities of fuzzy control.

In the fuzzy logic subprocess, the membership functions, as well as the fuzzy rules or linguistic rules, are established. Once these elements are set, the fuzzification process is applied to the inputs, which are values returned by the sensors, and the defuzzification process determines the value for the next state of the actuator.

2) LoRa configuration subprocess: The LoRa communication configuration consists of two stages:

- Internal parameter configuration (see Fig. 19).
- Message structure (see Fig. 20).

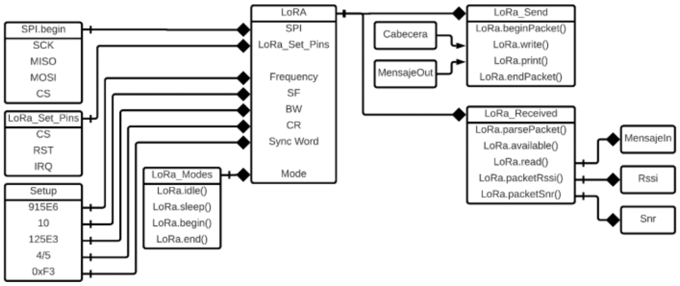

Fig. 19. Entity relationship of LoRa parameters.

For the configuration of internal parameters, the Entity Relationship of Fig. 19 is established, in which the same frequency, Spreading Factor (SF), Bandwidth (BW), Correction Rate (CR), and synchronization word (Init byte) are set for each device. The LoRa message sent has the same structure in different nodes, as shown in Fig. 20.

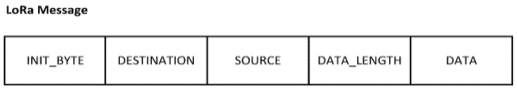

Fig. 20. LoRa message structure.

3) Subprocess of thingspeak configuration: Since the gateway node communicates with the cloud, it is necessary to establish the parameters for communication. This subprocess is described in the entity relationship of Fig. 21.

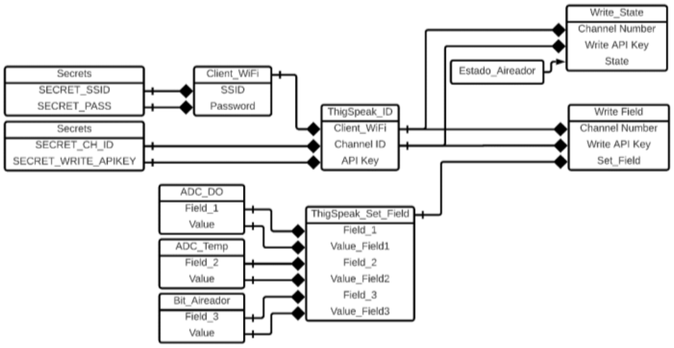

Fig. 21. Entity relationship of the thingspeak configuration subprocess.

The WiFi information, the channel to communicate with in ThingSpeak, and the API Key generated for communication are established. In this same scheme, it can be observed that when all the fields are ready and within the process flow, both a state is updated and fields are written to.

4) Sensor node: Since the sensor node is located inside the shrimp pond and operates autonomously, it requires better control over its operation time. Therefore, a reading interval of six hours is established for the process.

Pseudocode 2: Sensor node

```
Init
OD = 0;
Temp = 0;
ID_Coordinador = 0xID;
ID_Local = 0xID;
num_Case = 1;
Tiempo_A_Dormir = 21600; //21600 seconds = 6 hours
Void Setup {
        Serial.begin(115200);
        Display.begin();
        LoRa.setup();
        LoRa.begin();
}
Void loop {
        Switch (num_Case){
        case 1:
                DO = lecturaAnalogicaPonderada(pinDO);
                Temp = lecturaAnalogicaPonderada(pinTemp);
                num_Case ++;
                break;
        case 2:
                comunicacionLoRa(destino, origen, DO, Temp);
                num_Case++;
                break;
        case 3:
                num_Case =1;
                esp_deep_sleep_start();
                break;}}
```

5) Actuator node: Since the actuator node is directly powered by the control board, the equipment is always active. Its process involves reading the messages transmitted through a coordinator node, and depending on the case, it activates or deactivates the aerator.

Pseudocode 3: Actuator Node

```
Init
Aireador = 0;
ID_Coordinador = 0xID;
ID_Local = 0xID;
num_Case = 1;
Void Setup {
        Serial.begin(115200);
        Display.begin();
        LoRa.begin();
        pinMode(AireadorPin, OUTPUT);
}
Void loop {
        Switch (num_Case){
        case 1:
                LoRa_Read();
                If ( LoRa_Ok == True)
                        num_Case ++;
                } else  {
                        num_Case = 1;}
                break;
        case 2:
                if (Aireador == 1){
                    digitalWrite(aireadorPin, HIGH);
                } else {
                    digitalWrite(aireadorPin, LOW);}
                num_Case = 1;
                LoRa_Ok = false;
                break;
        }}
```

IV. RESULTS

In this section, the results obtained with the designed control and monitoring system are described. Fig. 22 illustrates the flow followed for the control of a shrimp pool.

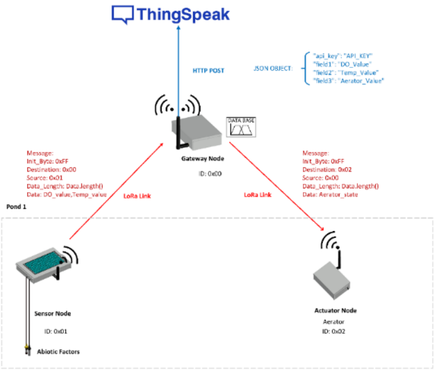

Fig. 22. Process of control in a shrimp pool.

In the embedded system of the coordinator node, linguistic terms, membership functions, antecedents, and consequents for fuzzy rules are established. In this study, three membership functions were applied, as shown in Fig. 23.

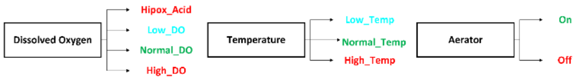

Fig. 23. Linguistic terms.

The embedded system uses fuzzy logic to represent the relevant linguistic terms. From these terms, three membership functions are generated: Dissolved Oxygen (see Fig. 24), Temperature (see Fig. 25), and Aerator (see Fig. 26). These membership functions capture the characteristics and variability of each variable in the system.

Fig. 24. Dissolved oxygen membership function.

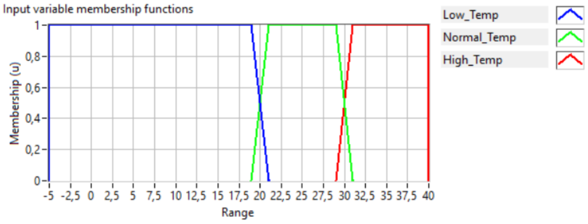

Fig. 25. Temperature membership function.

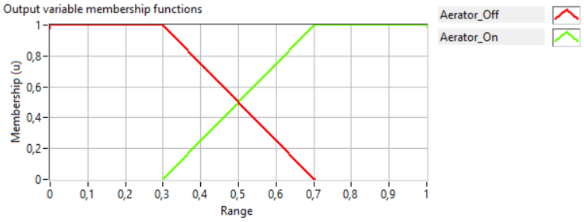

Fig. 26. Aerator membership function.

Since the fuzzy controller was implemented in an embedded system, the membership functions take a trapezoidal form, adapting to the limitations of the system. When establishing the membership functions, the values mentioned in Table II were taken into account. From these membership functions, the corresponding fuzzy rules were generated, which are shown in Fig. 27.

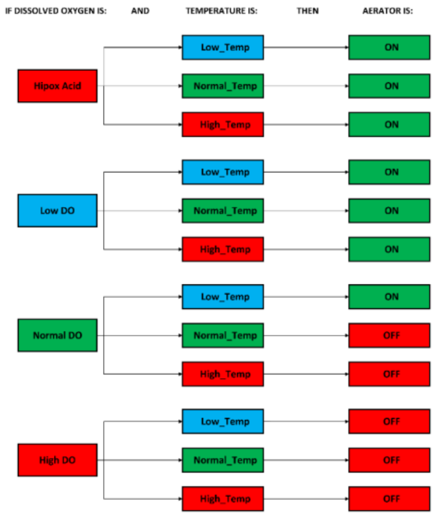

Fig. 27. Fuzzy Rules for the control system

The fuzzy rules used in this study were based on previous research [12], [13], [21]. From these established fuzzy rules, LabVIEW software was used to generate the fuzzy relation function, which reflects the expected behavior of the system. The fuzzy relation function was constructed based on the 12 defined fuzzy rules, and its response is shown in Fig. 28.

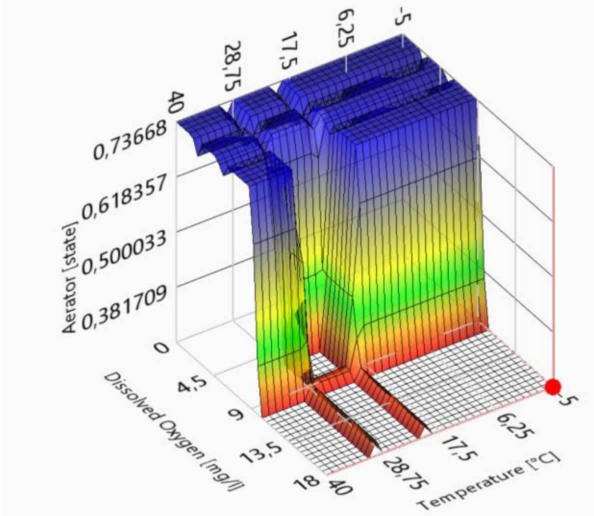

Fig. 28. Fuzzy rules.

In the coordinator node, a test was conducted with different values to verify the functionality, from which the results described in Table VI were obtained.

TABLE VI. FUZZY CONTROL RESPONSE

		Dissolved Oxygen (mg/L)												
		3.1	**3.5**	**3.9**	**4.5**	**5**	**6**	**7**	**8**	**8.5**	**9.5**	**10**	**11**	**15**
Temperature (°C)	**-5**	0.76	0.72	0.72	0.76	0.72	0.72	0.76	0.76	0.76	0.76	0	0	0
	10	0.76	0.72	0.72	0.76	0.72	0.72	0.76	0.76	0.76	0.75	0	0	0
	15	0.76	0.72	0.72	0.76	0.72	0.72	0.76	0.76	0.76	0.75	0	0	0
	20	0.76	0.72	0.72	0.76	0.72	0.72	0	0	0	0	0	0	0
	25	0.76	0.72	0.72	0.76	0.72	0.72	0	0	0	0	0	0	0
	30	0.76	0.72	0.72	0.76	0.72	0.72	0.65	0.65	0.65	0.65	0	0	0
	35	0.76	0.72	0.72	0.76	0.72	0.72	0.76	0.76	0.76	0.75	0	0	0

For the digital selection of the next state of the aerator, a threshold was established:

$$Aerator\ [state] > 0.5\ then\ Aerator\ ON$$

Considering the threshold described previously, the table of the control response is modified (see Table VII).

The fuzzy system implemented in the embedded system achieves the performance demonstrated in Fig. 29. The interaction of the abiotic parameters with the mechanical movement of the aerator can be observed. The goal is that when the abiotic parameters are within an optimal range, the aerator switches to an off state.

TABLE VII. CONTROLLER RESPONSE - AERATOR STATUS

		Dissolved Oxygen (mg/L)												
		3.1	**3.5**	**3.9**	**4.5**	**5**	**6**	**7**	**8**	**8.5**	**9.5**	**10**	**11**	**15**
Temperature (°C)	**-5**	1	1	1	1	1	1	1	1	1	1	0	0	0
	10	1	1	1	1	1	1	1	1	1	1	0	0	0
	15	1	1	1	1	1	1	1	1	1	1	0	0	0
	20	1	1	1	1	1	1	0	0	0	0	0	0	0
	25	1	1	1	1	1	1	0	0	0	0	0	0	0
	30	1	1	1	1	1	1	1	1	1	1	0	0	0
	35	1	1	1	1	1	1	1	1	1	1	0	0	0

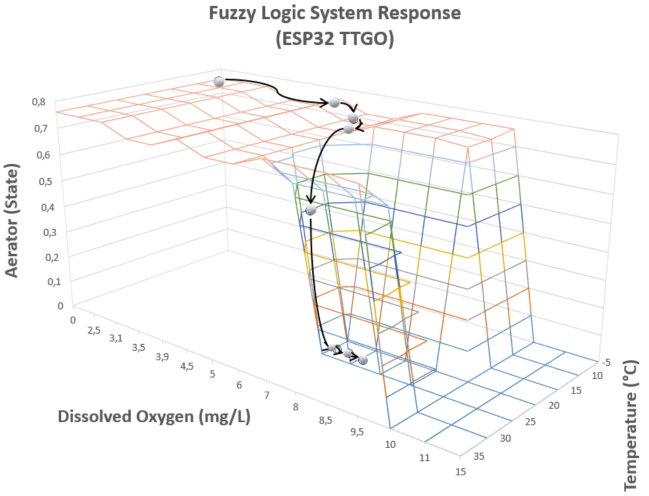

Fig. 29. Response of fuzzy logic according to abiotic factor.

V. CONCLUSIONS

The proposed control and monitoring system was established with the input of domain experts and reviewed research. However, it was observed that considering the needs of internal producers is of vital importance in order to encompass the required system activities and to determine the optimal solution based on available market equipment. It was determined that in order to operate within an IoT architecture, various situations and events must be taken into account. One of the key factors is the communication and security aspects that the equipment must possess, as well as the scalability they offer. Therefore, for the monitoring and control system established in this study, a star topology was considered for sensor and actuator nodes. This configuration allows for isolated points of connection, as establishing two-way communication requires higher processing and energy consumption.

Referring to the system's security levels, LoRa technology enabled the allocation of a specific channel, defining bytes for synchronization between devices. Additionally, fields were added to maintain control over transmissions and to determine the source and destination of messages. Identifying and discarding corrupted messages without processing them is crucial. To address this, a validation process was incorporated, which includes a field for assessing this condition.

The communication between the devices was successful in an urban environment of up to 1 km without packet loss, although it was necessary to adjust the LoRa configuration parameters to optimize performance. The use of fuzzy control based on abiotic factors allowed for effective control criteria in the shrimp pool, improving shrimp performance and growth through aerator control.

As future work, it is proposed to expand the number of abiotic factors without affecting performance and improve the range of the devices. An improvement option would be to migrate to a LoRaWAN network to take advantage of its additional benefits in terms of coverage and management capacity.

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